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Probing Spontaneous CP-Violation in Supersymmetric Models via B-Decays

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Abstract

We study implications of spontaneous CP-violation in minimal susy models for CP-asymmetries in rare B, \bar{B} -decays. In particular, we estimate characteristic values of the angles of the unitarity triangle and show that sizeable CP-violating effects result from $B - \bar{B}$ mixing only. Significant deviations from the SM predictions are pointed out.

1 Introduction

One of the most intriguing open questions in particle physics is understanding the origin of CP-violation. Even though the observable CP-violating effects in kaon decays can be accommodated within the Standard Model via the Cabibbo-Kobayashi-Maskawa (CKM) mechanism [1], the real nature of CP-violation is still to be uncovered.

A careful study of CP-violating effects in B-decays would reveal whether the CKM model provides an adequate description of CP-violation in nature. In particular, the CKM model implies the existence of a nondegenerate unitarity triangle [2]: the condition of orthogonality of the columns or rows of a unitary matrix can be represented by a triangle in the complex plane. The angles of this triangle correspond to the relative complex phases between the CKM matrix elements. For example, since sizeable complex phases are expected in the CKM matrix elements involving the first and third generations, a triangle formed by $V(ub)$, $V^*(td)$, and $-V(cb) \sin \theta_c$ should have relatively large angles: their typical values range from 15° to 145° (see, for example, [3]). Independent measurements of the sides and angles of this triangle would overdetermine the unitarity triangle allowing us to check explicitly the validity of the CKM approach. Any appreciable deviation from the Standard Model predictions would indicate the presence of “New Physics” such as the existence of a fourth family, supersymmetry, etc.

In this letter we study implications of an alternative to the CKM approach - a model in which CP-symmetry is broken spontaneously. In particular, we will consider minimal susy models and concentrate on CP-violating effects in B-decays which allow us to extract information about the angles of the unitarity triangle.

2 Spontaneous CP-violation in SUSY Models

The possibility of spontaneous CP-violation (SCPV) in the minimal susy models has recently drawn considerable attention [6-13]. The basic idea is that, in a general two Higgs doublet model, the Higgs fields can acquire complex VEV’s if the scalar potential is not Peccei-Quinn (PQ) invariant [4]. Phenomenologically acceptable susy models present a fertile ground for SCPV since they require the presence of at least two Higgs doublets.

In the minimal supersymmetric Standard Model (MSSM), the desired PQ-breaking terms can be generated only via radiative corrections [6] and, as a result of the Georgi-Pais theorem [5], such a scenario predicts the existence of a light axion. Consequently, even though SCPV is possible in the MSSM in principle [8,9], it is ruled out by experimental constraints on the mass of the lightest Higgs boson [7].

The next-to-minimal supersymmetric Standard Model (NMSSM) has been shown to be free of this problem [10] and is, at the moment, experimentally viable. The implications of this model for observable CP-violating effects in $K - \bar{K}$ systems were first studied by Pomarol [11]. He has shown that, in a favorable region of the parametric space, this scenario can predict correct values of ϵ and ϵ' while complying with the experimental bounds on the Neutron Electric Dipole Moment (NEDM). Our more recent analysis [12] showed that the requirement that the squarks be sufficiently heavy (300-400 GeV) allows one to enlarge the available region of the parametric space. Yet, even in this case some fine-tuning is required and the values of the CP-phases would have to be small: from 0.01 to 0.1.

The experimental information on CP-violation in $K - \bar{K}$ systems and constraints on the NEDM cannot distinguish between the CKM model and susy models with spontaneously broken CP. To discriminate against one of them, we have to combine these data with B-decay phenomenology. In what follows, we estimate the characteristic values of the angles of the unitarity triangle α_i in the context of spontaneous CP-violation in the NMSSM (or similar models). We will see that they are significantly different from their Standard Model counterparts.

3 CP-violation in B Decays

Let us consider nonleptonic B decays into CP eigenstates. The three angles of the unitarity triangle α_{1-3} ¹ can be probed, for example, via the following decays

$$B_d \rightarrow \psi K_s \sim \sin 2\alpha_1 , \quad (1)$$

$$B_d \rightarrow \pi^+ \pi^- \sim \sin 2\alpha_2 , \quad (2)$$

$$B_s \rightarrow \rho^0 K_s \sim \sin 2\alpha_3 . \quad (3)$$

¹We follow the notation of Ref.[3]

In these decays, CP-violation manifests itself as a deviation of the decay rate from a pure exponent $e^{-\Gamma t}$. Since the CKM model predicts enormous (up to 30%) CP-asymmetries [14], these decays offer excellent opportunities for observing large CP-violating effects. Neglecting a small² $B_L - B_H$ lifetime difference, the proper time evolution of the decay rate can be written as [3]

$$\Gamma(B^0(t) \rightarrow f_i) \propto e^{-\Gamma t} \left(1 - \sin 2\alpha_i \sin \Delta m t \right),$$

$$\Gamma(\bar{B}^0(t) \rightarrow f_i) \propto e^{-\Gamma t} \left(1 + \sin 2\alpha_i \sin \Delta m t \right),$$

with Δm being the $B_L - B_H$ mass difference. Here we have taken into account that [14]

$$\left| \frac{A(\bar{B}^0 \rightarrow f_i)}{A(B^0 \rightarrow f_i)} \right| \approx 1, \quad (4)$$

$$\left| \frac{q}{p} \right| \approx 1, \quad (5)$$

where p, q are the Pais-Treiman coefficients [15] defining the mass eigenstates in terms of the flavor eigenstates B^0, \bar{B}^0 . The CP-asymmetry results from an interference between the two processes

$$B^0 \rightarrow f_i \text{ and } B^0 \rightarrow \bar{B}^0 \rightarrow f_i,$$

and includes CP-violating effects in both mixing ($|\Delta B| = 2$) and decays ($|\Delta B| = 1$). The angles of the unitarity triangle can be expressed as

$$\sin 2\alpha_i = \eta_i^{CP} \operatorname{Im} \left[\frac{q}{p} \frac{\langle f_i | \mathcal{L}^{CP} | B^0 \rangle}{\langle f_i | \mathcal{L} | B^0 \rangle} \right] = -\eta_i^{CP} \sin(2\phi_{D_i} + \phi_M), \quad (6)$$

where η_i^{CP} denotes the CP-parity of the final state (-1 for ψK_s and $\rho^0 K_s$, and $+1$ for $\pi^+ \pi^-$) and ϕ_{D_i}, ϕ_M are the weak phases entering the $b \rightarrow q\bar{q}Q$ decay and $B - \bar{B}$ mixing diagrams, respectively. Note that no hadronic uncertainties are involved in this formula and, in the Standard Model, the α_i are functions of the CKM matrix elements only. Even though one cannot

²For the $B_s - \bar{B}_s$ system it is not negligible. The corresponding CP-asymmetry can be read off from the $e^{-\frac{1}{2}\Delta\Gamma t} \sin \Delta m t$ term in the decay rate evolution.

predict the exact values of these angles due to large uncertainties in the CKM matrix, eq.(6) allows us to verify generic features of the CKM approach such as the existence of the unitarity triangle. Should α_i not add up to 180° , the necessity for an alternative theory of CP-violation would be manifest. Thus, B decays into CP-eigenstates provide a useful and precise tool in the search for physics beyond the Standard Model.

4 Implications of Spontaneous CP-violation for B Decays

Let us now proceed to evaluating the angles $\{\alpha_i\}$ in the context of the NMSSM. This model includes the MSSM superfields along with an extra singlet superfield \hat{N} and was first introduced to rectify the so called “ $\mu - problem$ ” [16]. A list of relevant interactions can be found in Refs.[11] and [17].

We assume that the initial Lagrangian conserves CP and it is only the vacuum that breaks it. In the process of electroweak symmetry breaking the neutral Higgs components develop the following VEV’s:

$$\langle H_1^0 \rangle = v_1, \langle H_2^0 \rangle = v_2 e^{i\rho}, \langle N \rangle = n e^{i\xi} .$$

If ρ and/or ξ are not equal to an integer multiple of π , CP symmetry is violated. Through various interactions these complex phases will enter the mass matrices and interactions of the matter fields leading to observable CP-violating effects.

To estimate the consequent asymmetries in B decays, first we will have to find the weak phase ϕ_M coming from the $B - \bar{B}$ mixing diagram. Following the line of Ref.[11], we adopt the following super-CKM ansatz (a squark version of the CKM matrix)

$$\tilde{V} \approx \begin{pmatrix} 1 & O(\epsilon) & O(\epsilon^2) \\ O(\epsilon) & 1 & O(\epsilon) \\ O(\epsilon^2) & O(\epsilon) & 1 \end{pmatrix} \quad (7)$$

Here ϵ is of the order of Cabibbo mixing angle θ_C . Note that all the entries are real since we are considering spontaneous CP-violation.

The real part of the $B - \bar{B}$ mixing is dominated by the SM box and chargino super-box diagrams (Fig.1a,b). For simplicity, we assume that the gluino is sufficiently heavy and its contribution to the $B - \bar{B}$ mixing is negligible.³ There are three major contributions to the imaginary part of the $B - \bar{B}$ mixing coming from the CP-violating diagrams in Fig.2a,b and c. The box diagram with Higgs exchange (Fig.2a) involves a complex phase in the top quark mass insertion (this phase, of course, can be absorbed into the Higgs vertex by a phase redefinition of t_R). However, this diagram is suppressed by a factor of $(m_b/m_W)^2$ and can safely be neglected. The diagrams in Fig.2b,c contain phases in propagators of the superparticles. In the case of $K - \bar{K}$ system, an analog of the diagram 2b is responsible for a nonzero value for $\text{Re } \epsilon$ [11]. To estimate its effect for the $B - \bar{B}$ system, we can repeat the $K - \bar{K}$ mixing analysis with heavy squarks $m_{\tilde{q}}^2 \gg m_{\tilde{W}}^2$ [12]. Note that the diagram 2c, which did not play any role for the $K - \bar{K}$ system, can give a significant contribution to the imaginary part of the $B - \bar{B}$ mixing. The corresponding $\Delta B = 2$ operator is given by

$$O_{\Delta B_q=2} = (k_q + e^{i\phi} l_q + e^{2i\phi} l'_q) \bar{d} \gamma^\mu P_L b \bar{d} \gamma_\mu P_L b, \quad (8)$$

where k_q , $e^{i\phi} l_q$ and $e^{2i\phi} l'_q$ ($q = d, s$) result from the diagrams shown in Fig.1, Fig.2b and Fig.2c, respectively. The weak phase ϕ is a function of the complex phases of the Higgs VEV's and is constrained to be between 0.01 and 0.1 (for the sake of definiteness, we assume it to be positive) from the $K - \bar{K}$ and NEDM analyses [11,12].

The Standard Model contribution is well known [19] and can be approximated by

$$k_q^{SM} \approx \frac{g^4}{256\pi^2 M_W^2} (V_{tb} V_{tq})^2. \quad (9)$$

Assuming that the first and second generation squarks are degenerate in mass and the stop mass is different, we estimate the super-box contribution (Fig. 1b) to be [18]

$$k_q^{susy} \approx \frac{g^4}{192\pi^2 m_{\tilde{q}}^2} (\tilde{V}_{tb} \tilde{V}_{tq})^2 \quad (10)$$

³As long as the gluino contribution does not dominate the $B - \bar{B}$ mixing, the essential results of this paper remain unchanged.

with $m_{\tilde{q}}^2$ being the average squark mass. The CP-violating super-box (Fig.2b) generates [12]

$$l_q \approx \frac{g^4}{128\pi^2} \left(\frac{gm_t}{\sqrt{2}m_W \sin\beta} \right)^2 \frac{v z m_{LR}^2}{m_{\tilde{W}} m_{\tilde{q}}^4} (\tilde{V}_{tb}\tilde{V}_{tq})^2 . \quad (11)$$

Here $z \sim 1$ is a partial cancellation factor [11]; $v = \sqrt{v_1^2 + v_2^2}$; $m_{\tilde{W}}$ and m_t denote the chargino and top quark masses, respectively; m_{LR} is the left-right squark mixing, and $\tan\beta = v_2/v_1$. Finally, the diagram in Fig.2c gives rise to

$$l'_q \approx \frac{g^4}{256\pi^2} \left(\frac{gm_t}{\sqrt{2}m_W \sin\beta} \right)^4 \frac{v^2 z' m_{LR}^4}{m_{\tilde{q}}^8} (\tilde{V}_{tb}\tilde{V}_{tq})^2 . \quad (12)$$

The factor $z' \sim 1$ results from the diagram 2c in which positions of \tilde{t}_L and \tilde{t}_R (as well as \tilde{W} and \tilde{H}) are interchanged. Such a diagram contributes with opposite phase and leads to a partial cancellation.

To estimate a relative size of these couplings, let us assume a maximal left-right mixing, $\tan\beta \sim 1$, $m_{\tilde{W}} \sim 100\text{GeV}$ and $m_{\tilde{q}} \sim 300\text{GeV}$. Using the super-CKM ansatz (7), it is not hard to see that

$$l_d, l'_d \ll k_d , \quad (13)$$

$$l_s, l'_s \sim k_s . \quad (14)$$

An appreciable contribution of the CP-violating super-box to the $B_s - \bar{B}_s$ mixing is an artifact of the chosen super-CKM form (7). However, it reflects a general tendency for models in which the mixing between the second and third generation squarks is enhanced as compared to that of quarks.

As a result, the $O_{\Delta B_s=2}$ operator attains an overall phase factor of $e^{iO(\phi)}$ and the corresponding weak phases are

$$\begin{aligned} \phi_M(B_s) &\sim \phi , \\ \phi_M(B_d) &\sim 0 , \end{aligned} \quad (15)$$

with $\phi \leq 0.1$.

Now we can proceed to calculating the remaining weak phase ϕ_{D_i} . In the Standard Model, the $b \rightarrow q\bar{q}Q$ decay is dominated by the tree level process (Fig.3) and the weak phase results from the complex CKM matrix

elements entering the vertices. However, in our case these entries are real. CP-violation must enter through a loop effect. The simplest 1-loop diagram which involves complex phases in the propagators of the superpartners is shown in Fig.4 (it is a version of the so called “Superpenguin” diagram). Its $s \rightarrow q\bar{q}d$ analog was calculated in [11,12] and shown to successfully describe the observed value of ϵ' in K decays. To get the corresponding 4-fermion effective interaction for the $b \rightarrow u\bar{u}d$ decay, we simply need to change the super-CKM entries at the vertices. Then, in the case $m_{\tilde{q}}^2 \gg m_W^2$, we obtain [12]

$$O_{\Delta B=1}^{s.p.} = e^{i\phi} |f| \bar{d}_L \gamma_\mu T^a b_L \bar{q}_R \gamma^\mu T^a q_R , \quad (16)$$

with

$$|f| \leq \frac{g_3^2 g^2}{576\pi^2} \left(\frac{gm_t}{\sqrt{2}m_W \sin\beta} \right)^2 \frac{v m_{LR}^2}{m_{\tilde{q}}^5} |\tilde{V}_{td}\tilde{V}_{tb}| . \quad (17)$$

Here g_3, g are the strong and weak couplings, respectively. It is easy to see that for a reasonable choice of the parameters ($\tan\beta \sim 1$, $m_{\tilde{q}} \sim 300\text{GeV}$, $m_{LR}/m_{\tilde{q}} \leq 1$) the effective coupling f is negligible as compared to the Fermi constant which describes the tree level process in Fig.3. The same argument equally applies to the decay mode $b \rightarrow c\bar{c}s$. Hence, direct CP-violating effects in decay processes are strongly suppressed and the weak decay phases $\phi_{D_{1-3}}$ can be neglected. All CP-violation in our scenario has to come from the $B - \bar{B}$ mixing and, consequently, there is a universal phase which describes all CP-violating effects. This is known as a *superweak* scheme of CP violation [20].

As a result, no CP-violation can be observed in $B_d - \bar{B}_d$ systems. Eq.(6) now takes on the form

$$\begin{aligned} \sin 2\alpha_1 &\approx 0 , \\ \sin 2\alpha_2 &\approx 0 , \\ \sin 2\alpha_3 &\approx \sin \phi . \end{aligned} \quad (18)$$

Apparently, the $\{\alpha_i\}$ fail to add up to 180° . However, the discrepancy can be too small to be detected: since $\phi \sim 0.1$ the α_3 is no larger than a few degrees.

So far we have considered the implications of SCPV using a specific form of the super-CKM matrix (7). With a more general super-CKM matrix, one naturally distinguishes two possibilities:

1. The CP-asymmetries in B, \bar{B} decays are negligible leading to a flat unitarity triangle (this, for example, happens when the super-CKM matrix duplicates the standard CKM matrix). This is very different from the SM prediction since, in the CKM model, all angles of the unitarity triangle are typically larger than 10° [21].

2. CP-violation in B decays is noticeable. Then some of the angles α_i are measurably different from zero (this requires a favorable super-CKM matrix, for example, (7)). Since direct CP-violation is negligible in this model, eq.(6) takes on the form

$$\begin{aligned}\sin 2\alpha_1 &= \sin \phi_1 , \\ \sin 2\alpha_2 &= -\sin \phi_1 , \\ \sin 2\alpha_3 &= \sin \phi_2\end{aligned}\tag{19}$$

where $\phi_{1,2} \leq 0.1$. This case is represented by a squashed “triangle” formed, for example, by $\phi_1/2$, $\pi - \phi_1/2$, and $\phi_2/2$. A deviation of $\alpha_1 + \alpha_2 + \alpha_3$ from 180° can be as large as a few degrees. This is a direct contradiction to the Standard Model.

In both cases the deviations from the SM predictions are significant. Note that the CP-asymmetries in this model are quite small. That happens because the same phase is responsible for both the NEDM and the CP-violating effects in neutral meson systems. Since the EDM of individual quarks is generated already at one loop level, the CP-violating phase has to be small to comply with the experimental bound on the NEDM. As a result, large CP-asymmetries cannot be accommodated within this model.

Another signature of spontaneous CP-violation may come from independent measurements of the sides of the unitary triangle: $|V(ub)|$, $|V(td)|$, and $|V(cb)\sin\theta_c|$. Since CP-violation and quark mixing have different origins in SCPV models, the relative values of these quantities do not have to be consistent with the angles $\{\alpha_i\}$. In fact, $|V(ub)|$, $|V(td)|$, and $|V(cb)\sin\theta_c|$ must form a completely flat triangle because all the CKM entries have to be real. This observation combined with the constraints on $\{\alpha_i\}$ provides a very sensitive probe of the model.

To summarize, we have analyzed implications of spontaneous CP-violation

in the simplest supersymmetric models for observable CP-asymmetries in B -decays. We have argued that the SCPV approach realizes the *superweak* scenario of CP-violation: all CP-violating effects are due to $B - \bar{B}$ mixing. The expected asymmetries are significantly smaller than those predicted by the Standard Model. A drastic deviation from the SM predictions can, in principle, be observed in decays (1)-(3): the corresponding CP-phases do not form the unitarity triangle (this, however, would require quite precise experimental data).⁴

Finally, it is worth mentioning that if both spontaneous and (super-)CKM mechanisms of CP-violation are present then the former can be responsible only for small corrections to the SM values of the angles $\{\alpha_i\}$. Since a deviation of $\alpha_1 + \alpha_2 + \alpha_3$ from 180° due to SCPV does not exceed a few degrees, this model would be indistinguishable from a susy model with general complex squark mixings [3].

To conclude, we see that a thorough study of B -phenomenology can reveal the origin of CP-violation and shed light on the source of new physics.

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⁴Large CP-asymmetries in B, \bar{B} decays ($\sin 2\alpha_1 \geq 0.4$) recently reported by CDF collaboration [22] suggest that SCPV is not likely to be the only source of CP-violation. However, the statistics at this time does not preclude the scenario discussed in this paper.

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Figure Captions

Fig. 1a,b Major contributions to the $B - \bar{B}$ mixing.

Fig. 2a,b,c Leading CP-violating contributions to the $B - \bar{B}$ mixing (all possible permutations are implied).

Fig. 3 Dominant contribution to $b \rightarrow q\bar{q}Q$.

Fig. 4 Leading CP-violating contribution to $b \rightarrow q\bar{q}Q$ (all possible positions of the left-right mixing are implied).